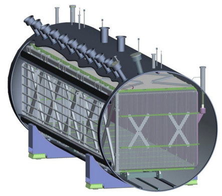


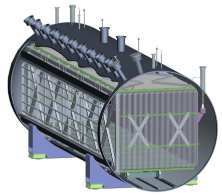
Space Charge Effect at MicroBooNE: Initial Studies

Michael Mooney, Xin Qian, Craig Thorn

Brookhaven National Laboratory

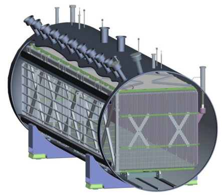
BNL MicroBooNE Analysis Tools Meeting

November 20th, 2014



Introduction

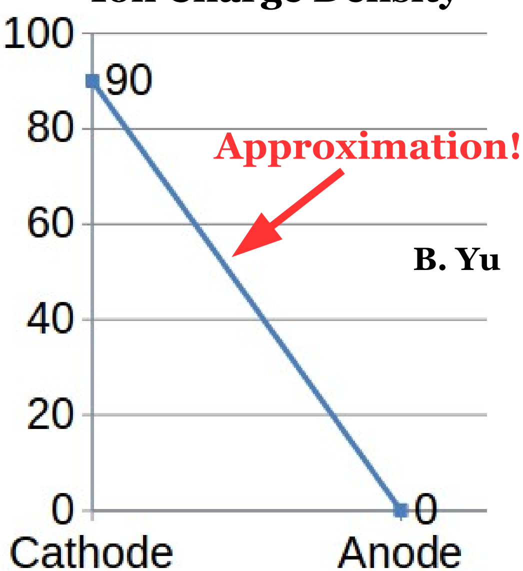
- Brief discussion today on new tool developed to study space charge effect at MicroBooNE
  - Focus is tool itself and preliminary results
  - Further discussion of possible use in calibrations/simulations in future meeting
- Outline:
  - Brief review of space charge effect
  - Ideas for calibration/simulation of effect
  - Development of code suite: **SpaCE** (Space Charge Estimator)
- Also see Randy Johnson's talks for more information: MicroBooNE Doc DB **#3838**, **#3839**

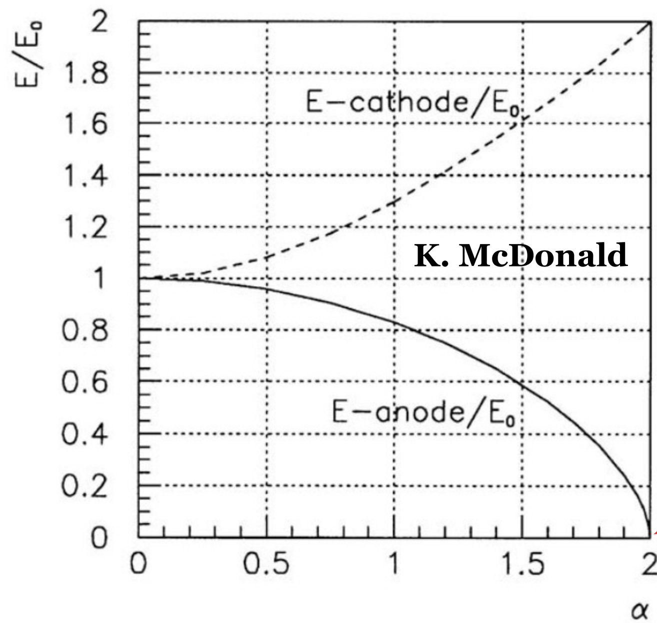


Space Charge Effect

- **Space charge**: excess electric **charge** (slow-moving ions) distributed over region of **space** due to cosmic muons passing through the liquid argon
  - Modifies E field, thus track/shower reconstruction
  - Effect not currently accounted for at MicroBooNE!
  - For neutrino experiments: effect **worst** at MicroBooNE!!

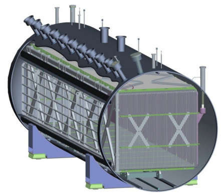
Ion Charge Density





$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

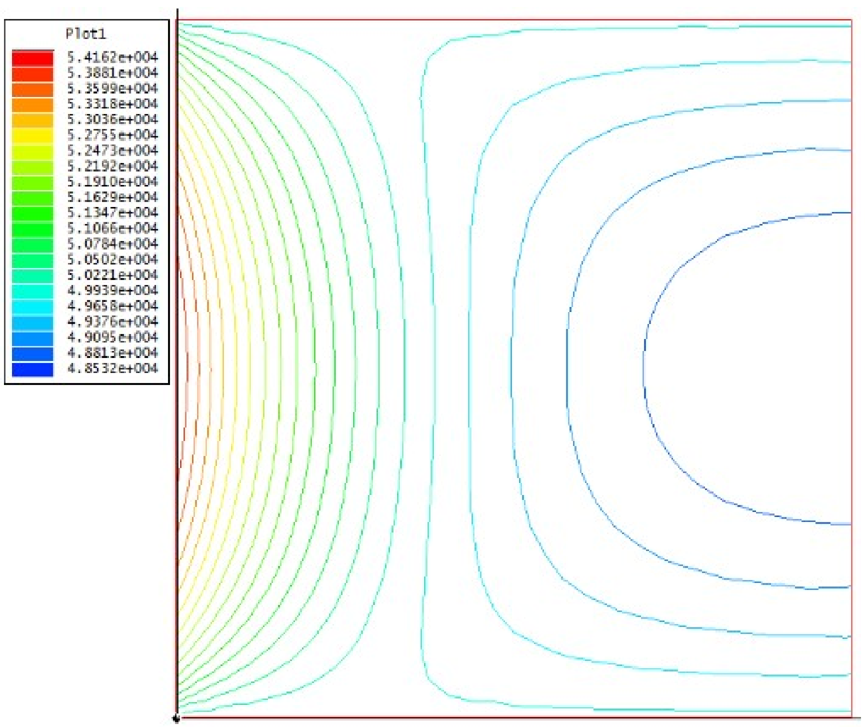
$$\mathbf{v} = \mu\mathbf{E}$$



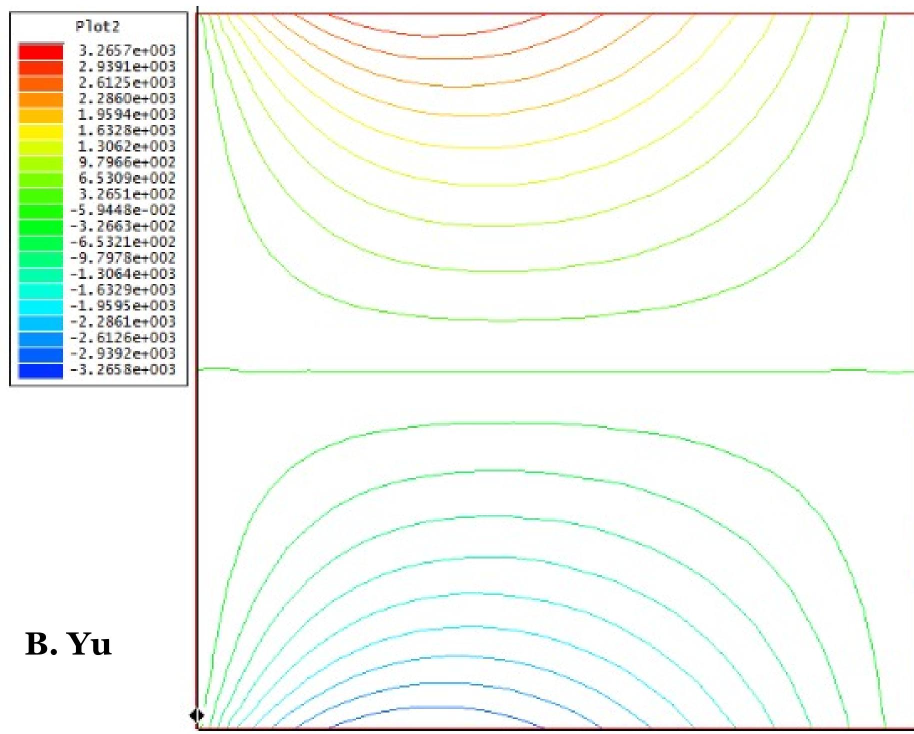
Impact on E Field

- Visualization of impact on E field (Bo Yu's 2D studies)
- Assumptions so far:
  - Constant charge deposition rate throughout detector
  - No liquid argon flow – **serious complication, needs addressing**

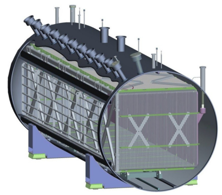
Drift Direction



Lateral Directions

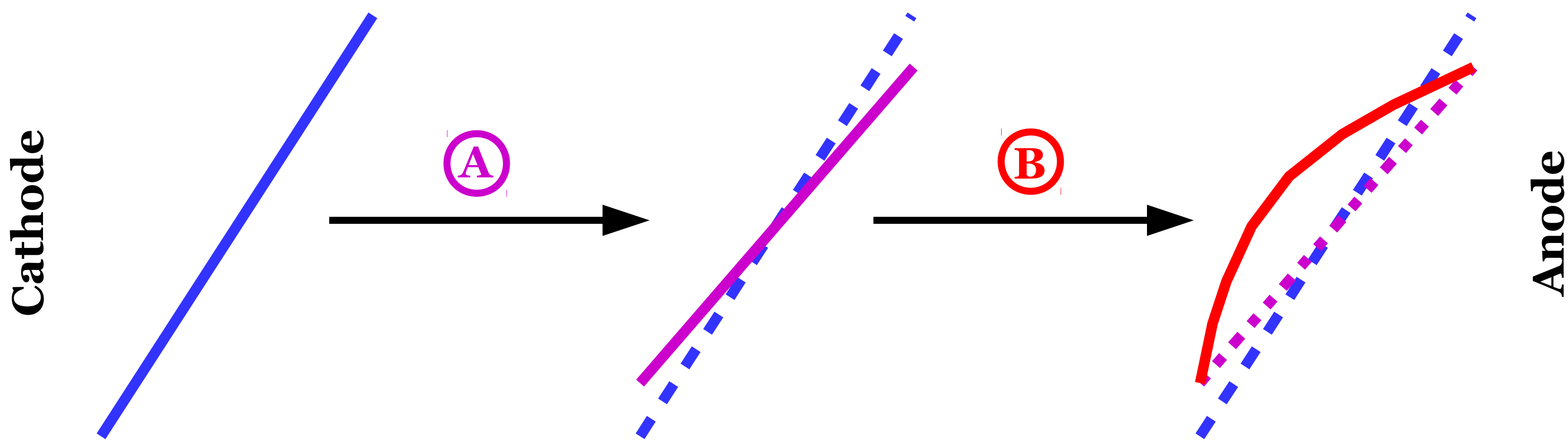


B. Yu



Impact on Track Reco.

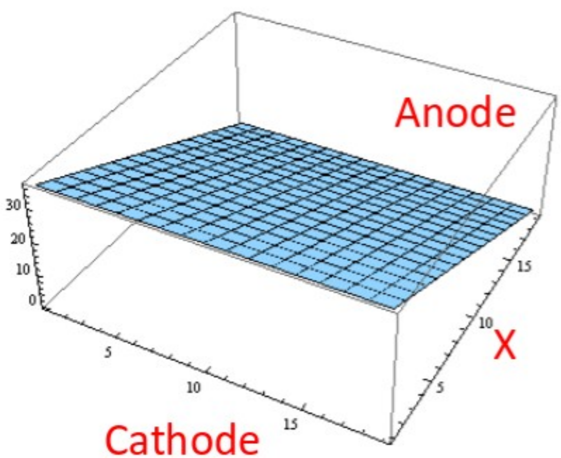
- Two separate effects on reconstructed **tracks**:
  - A • Reconstructed track shortens laterally (looks rotated)
  - B • Reconstructed track bows toward cathode (greater effect near center of detector)
- Once understand magnitude/variation of effect (ideally with data), can modify functional form of reconstructed track fit



Option 2
Time Distortions Only

Ref: Palestini and McDonald, LBNE DocDB #563-v2

Positive Ions across Detector



$$\rho_+ = \frac{Kx}{v_+} = \frac{Kx}{\mu_+ E}$$

K = generation rate

μ_+ = positive ion mobility

E_A = field at anode plane

$$E(x) = \sqrt{E_A^2 + \frac{Kx^2}{\varepsilon\mu_+}}$$

$$V = \int_0^L E(x)\,dx = \int_0^L \sqrt{E_A^2 + \frac{Kx^2}{\varepsilon\mu_+}}\,dx$$

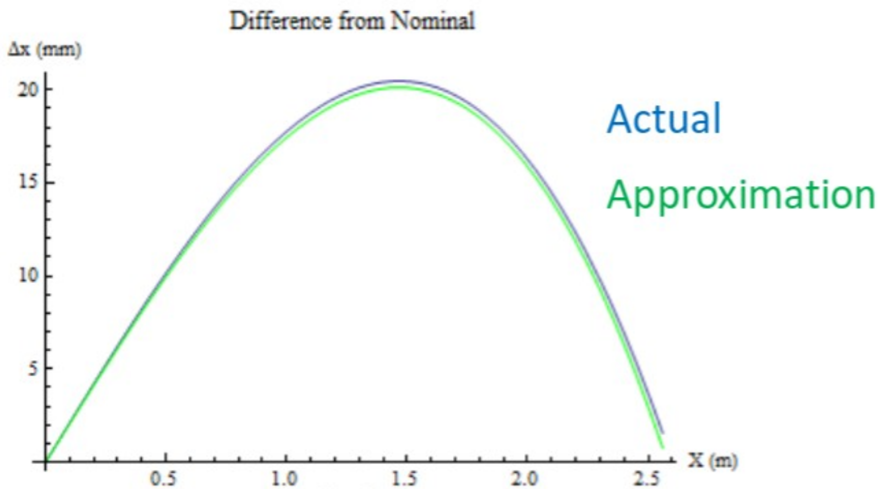
Invert to find E_A

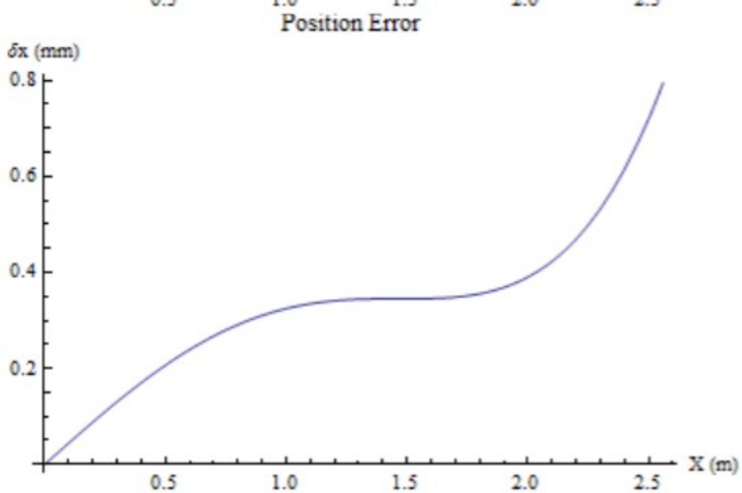
$$\Delta x_e = v_{\text{nom}}\left(\int_0^x \frac{1}{v_e(E(x))}dx - \frac{x}{v_{\text{nom}}}\right)$$

$$\approx \int_0^x -\frac{v_e(E(x)) - v_{\text{nom}}}{v_{\text{nom}}} + \left(\frac{v_e(E(x)) - v_{\text{nom}}}{v_{\text{nom}}}\right)^2 + \cdots dx$$

Slide Credit:
Randy Johnson

Option 2
Position Error





$$\Delta x_e = v_{\text{nom}} \left(\int_0^x \frac{1}{v_e(E(x))} dx - \frac{x}{v_{\text{nom}}} \right)$$

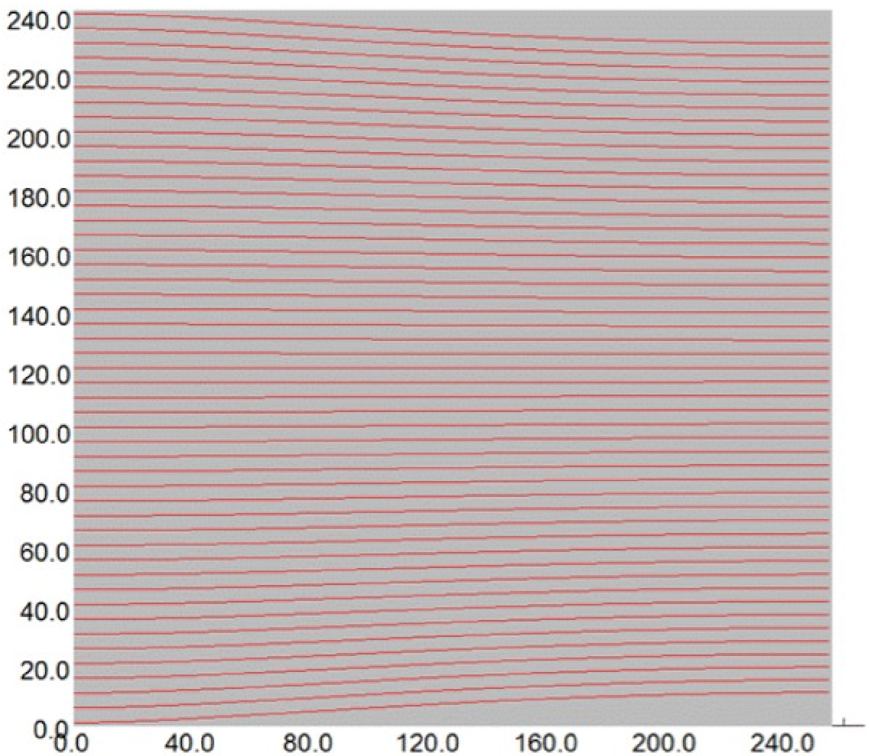
$$\approx \int_0^x -\frac{v_e(E(x)) - v_{\text{nom}}}{v_{\text{nom}}} + \left(\frac{v_e(E(x)) - v_{\text{nom}}}{v_{\text{nom}}} \right)^2 + \cdots dx$$

Approximation is integrable.

Slide Credit:
Randy Johnson

Randy's Proposal (cont.)

Option 3
Full One-to-One Mapping



Outside of LArSoft:

- Determine positive ion density
  - Include LAr drift (?)
- Finite element to determine E(x)
- Make mapping matrix $\{x,y,z\} \rightarrow \{t,y_w,z_w\}$

Inside of LArSoft:

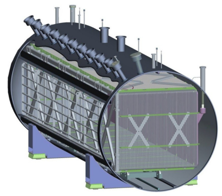
- Read in mapping matrix
- Use to determine $\{t,y_w,z_w\}$

<u>Slide Credit</u>:
Randy Johnson

Calibration/Simulation Ideas

BROOKHAVEN NATIONAL LABORATORY

- Randy and the UC group have proposed full one-to-one mapping matrix for each event
- Possible difficulties:
  - Addressing of liquid argon drift
  - Synchronization of calibration and simulation
  - Details of the implementation
- We would like to develop a correction addressing these important details:
  - Attempt to address liquid argon drift (both time-independent and time-dependent features) with data-driven calibration using cosmics and laser system
  - Represent effect in simulations by injecting data-driven calibration results into simulation – calibration and simulation intertwined
  - Development of code suite to study effect and eventually make corrections – **SpaCE** (see following slides)

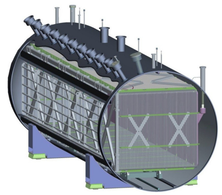


New Code Suite: SpaCE

- To study effect, develop new code suite: **SpaCE** (Space Charge Estimator)
  - Study **simple problems** first in detail with dedicated simulations
  - Maintain complete control over simulation chain for now – no LArSoft, no ANSYS, only code we develop (thus fully understand)
  - Eventually can network with LArSoft to extract correction factors from calibration and to simulate effect in MC

SpaCE:

The Final Frontier

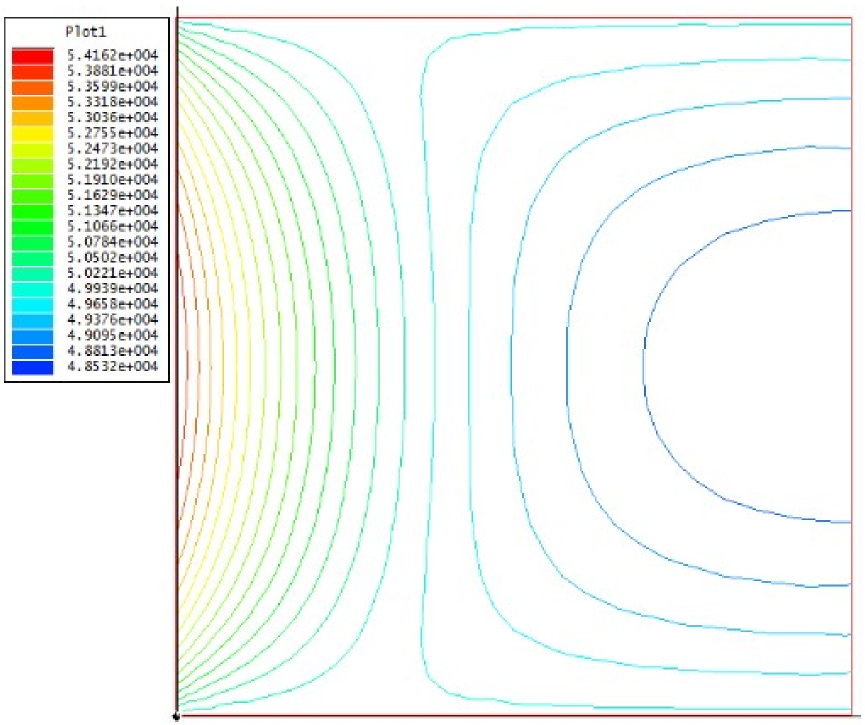


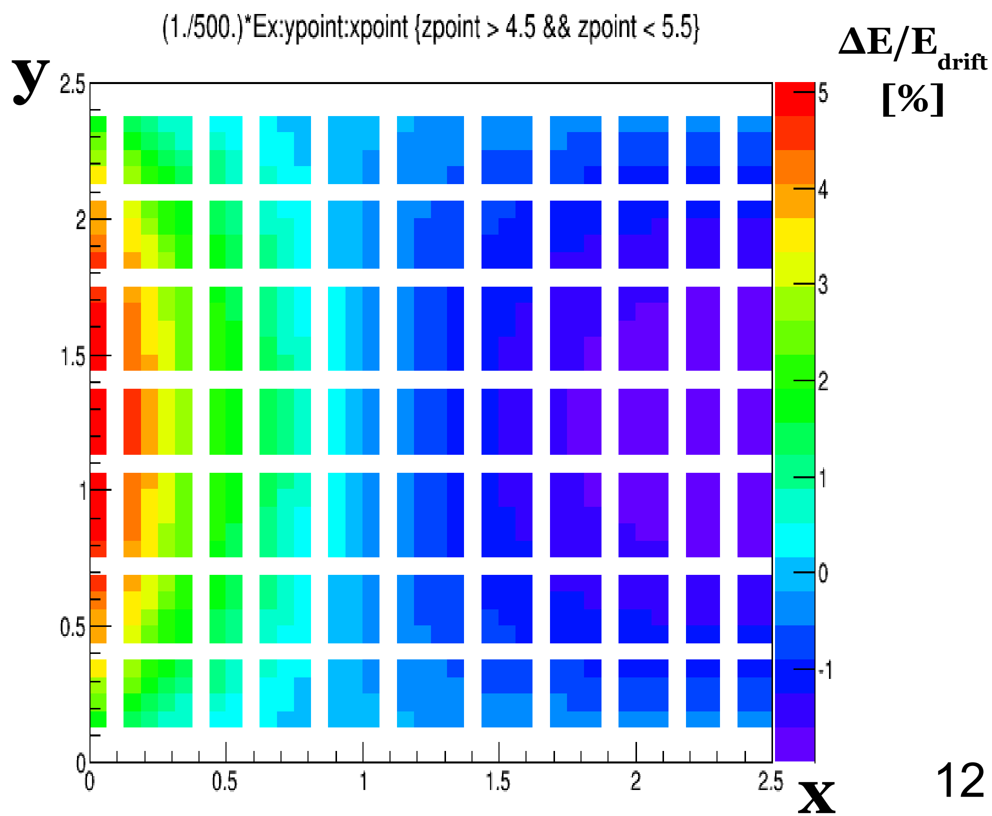
SpaCE Features

- So far have implemented effects of uniform space charge deposition without liquid argon flow
  - Linear space charge density approximation for now
- Obtain E fields analytically (in 3D space) via Fourier series solution to Poisson's equation
  - Calculate fields at finite set of points in 3D space
  - Keep only finite number of solution terms
  - Use more iterations near boundaries (due to $\sin[(n\pi x)/L]$ terms)
- Use interpolation scheme to obtain E fields in between solution points
  - Radial Basis Functions (RBF)
- Use ray-tracing technique to calculate electron drift time
  - RKF45 method

Comp. to Bo's Results: E_x

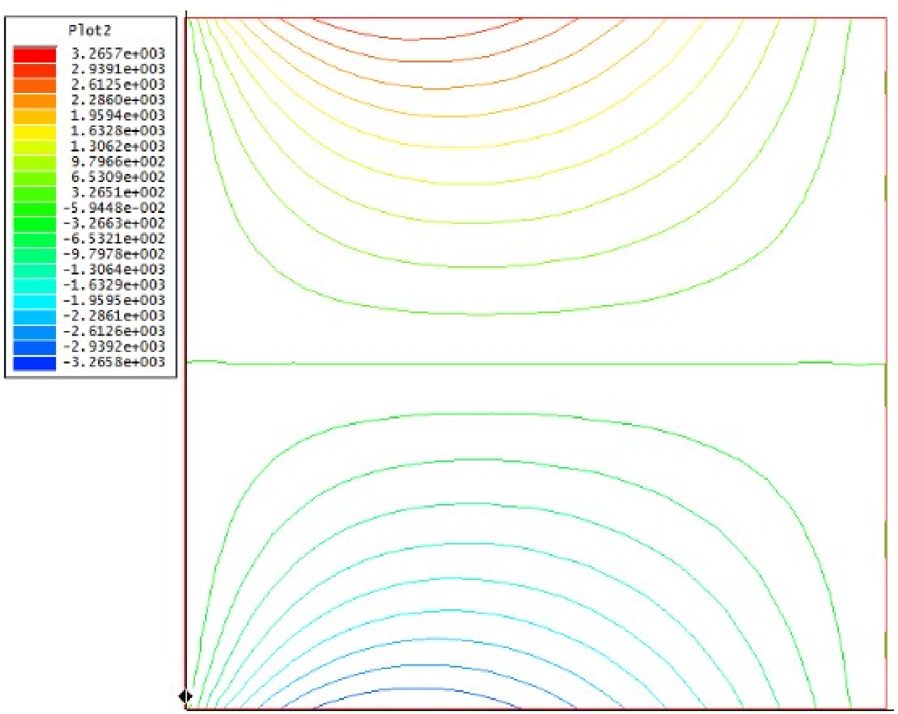
- Looking at central z slice (4.5 m < z < 5.5 m) in x-y plane
- Very good shape agreement
  - But boundaries left off here (within 0.1 m of edges in y/z directions)
- Normalization differences understood (using different rate)

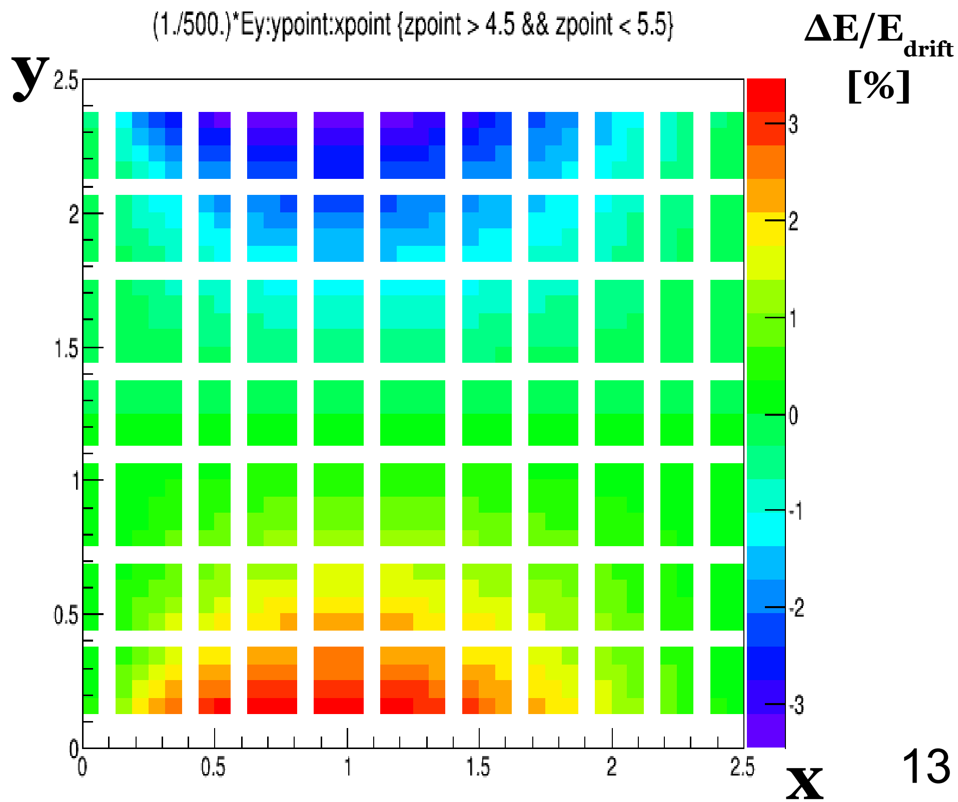




Comp. to Bo's Results: E_y

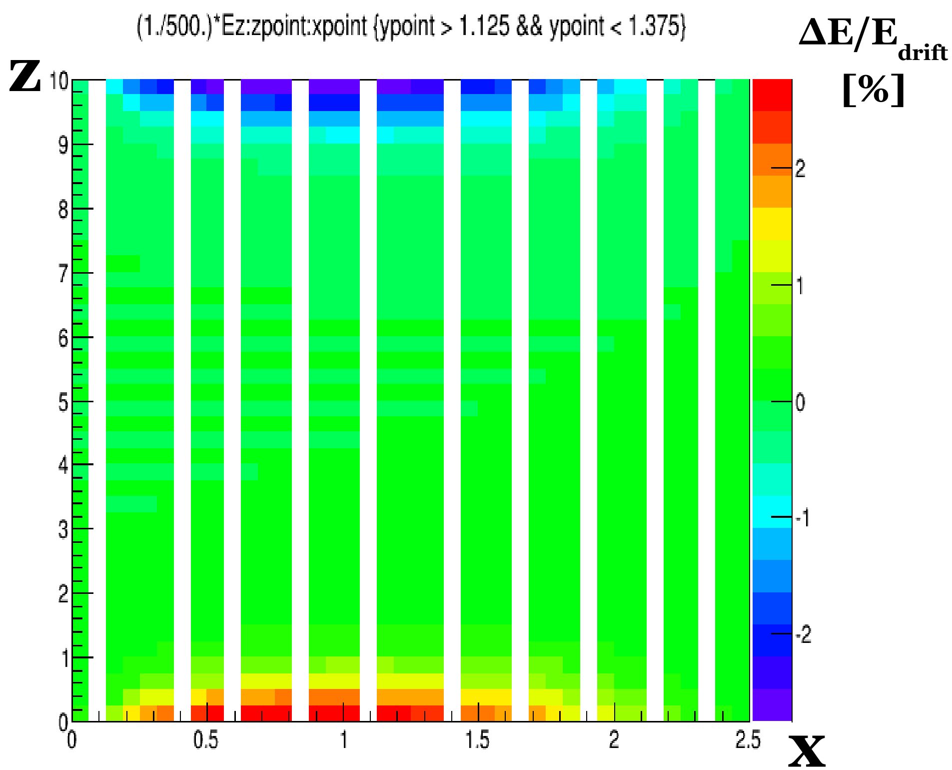
- Again looking at central z slice (4.5 m < z < 5.5 m) in x-y plane
- Very good shape agreement here as well
  - Parity flip due to difference in definition of coordinate system

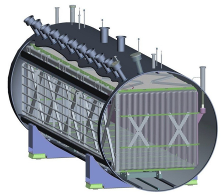




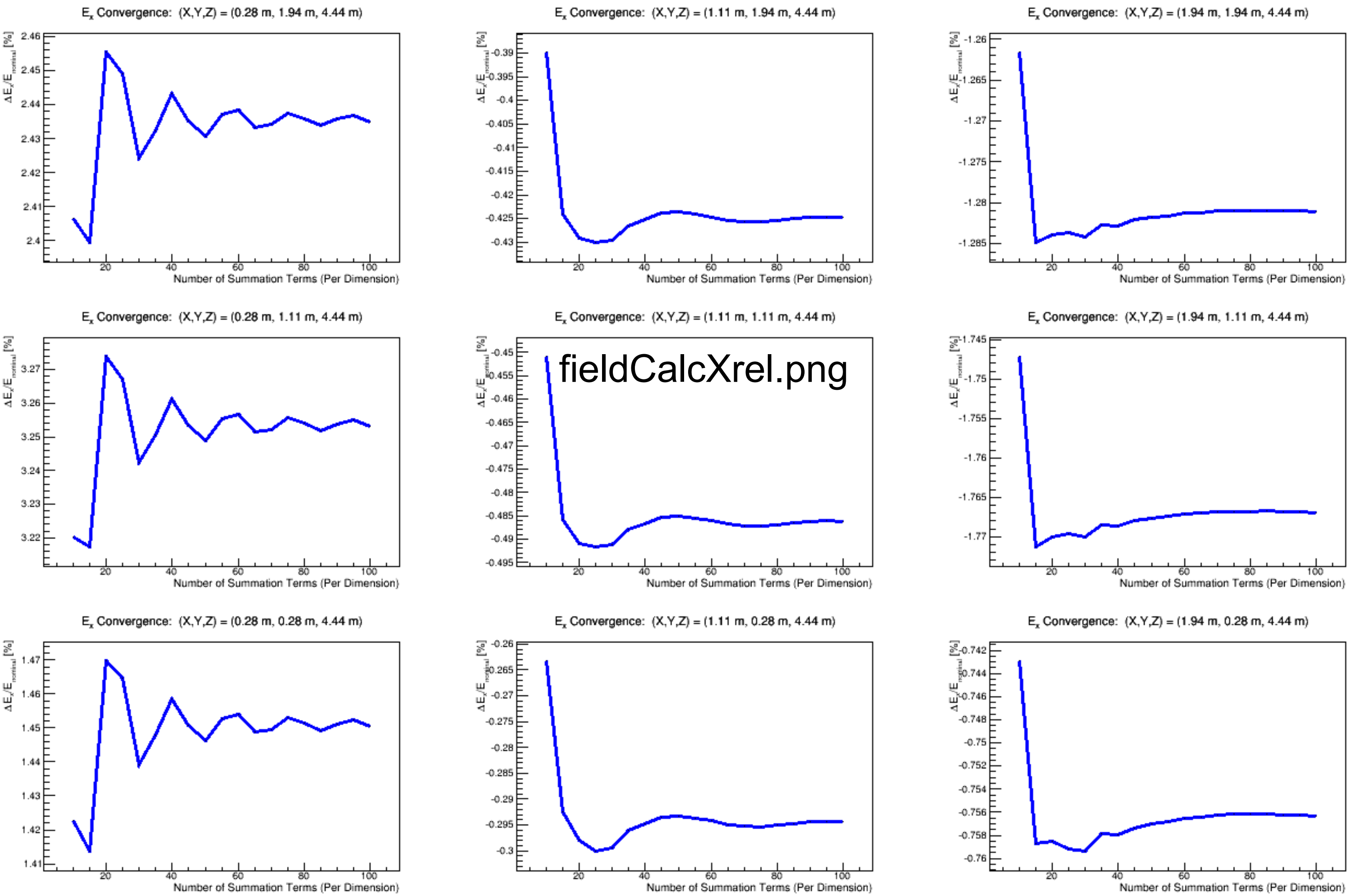
New Distribution: E_z

- Now looking at central y slice (1.125 m < y < 1.375 m) in x-z plane
- Much smaller field distortion in comparison with E_y
  - Due to less edge effects (**10 m** vs. **2.5 m**)

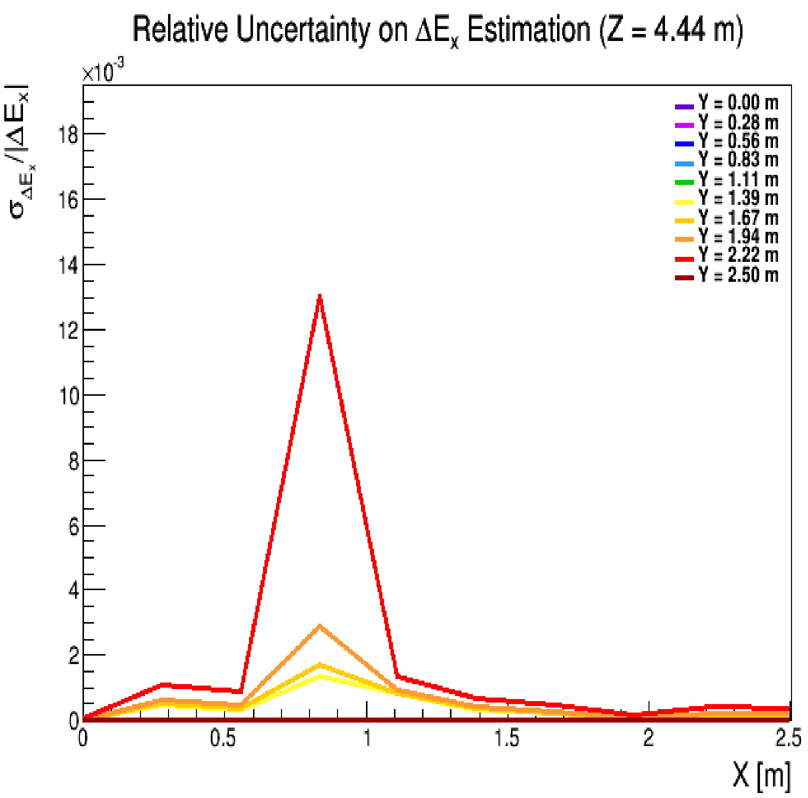


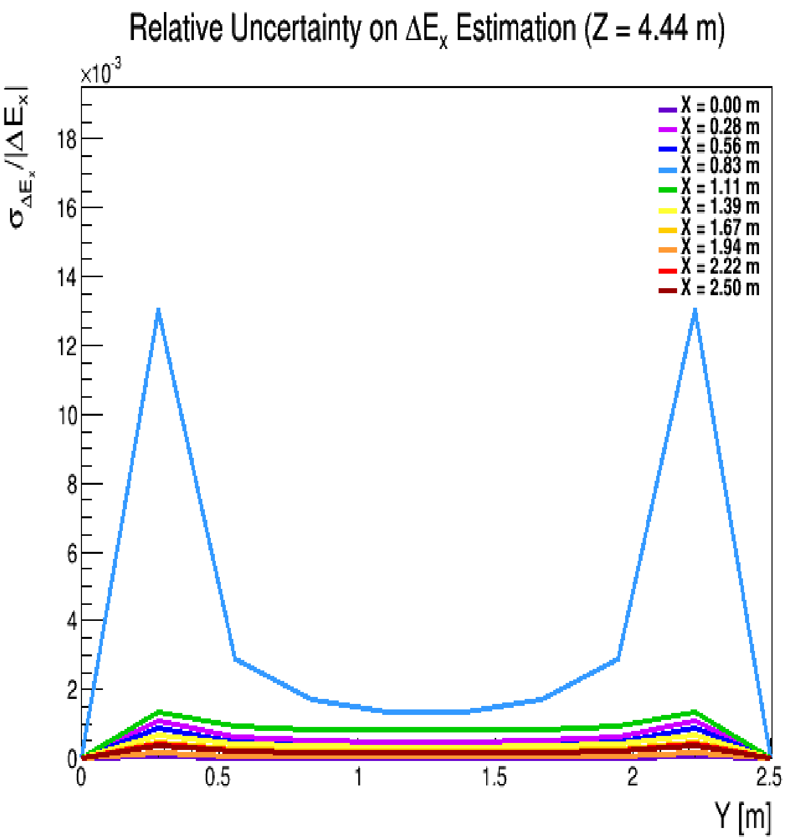


E Field Calc. Uncertainty



E Field Calc. Uncertainty

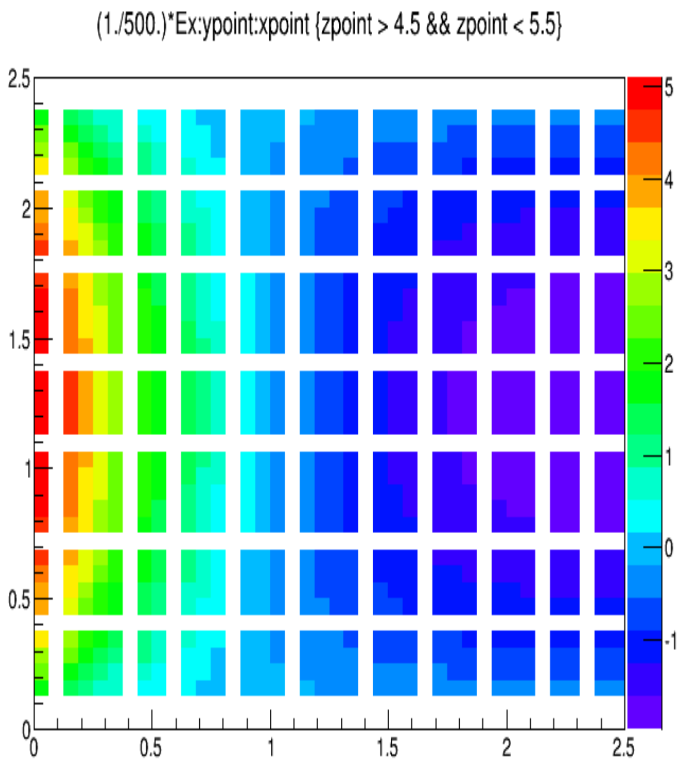


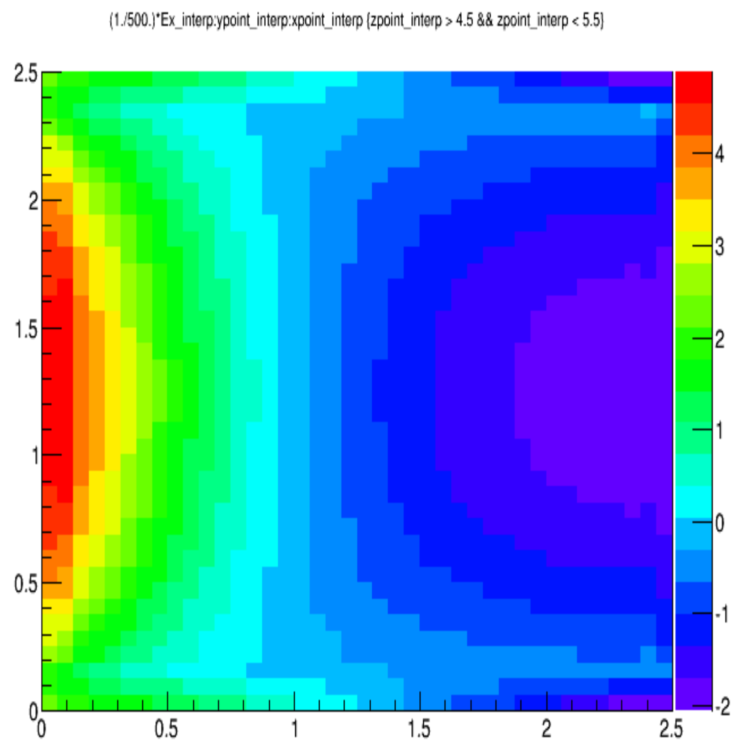


E Field Interpolation

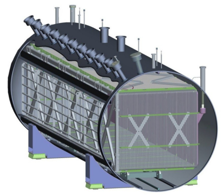
- First attempts at E field interpolation using RBF (Radial Basis Functions) via ALGLIB package
- Good matching so far, but interpolation does fairly poorly at edges – plan: include solution points at boundary in model

E_x
Before
Interp-olation



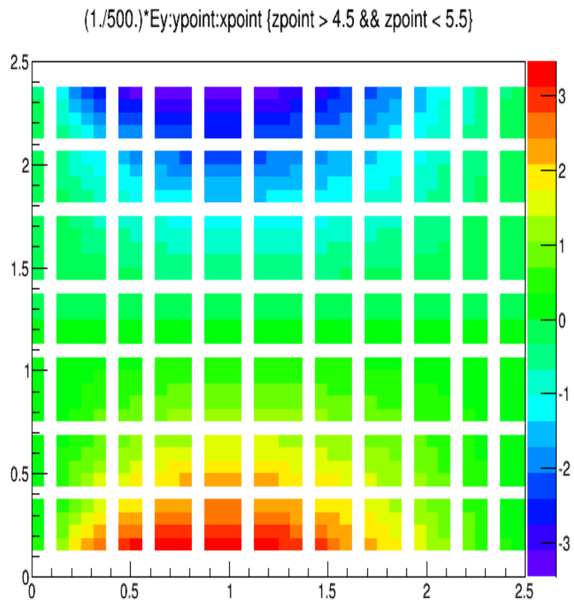


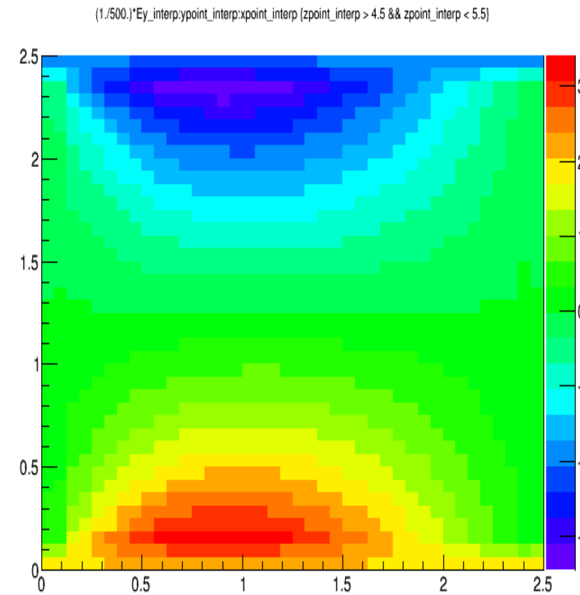
E_x
After
Interp-olation



E Field Interpolation (cont.)

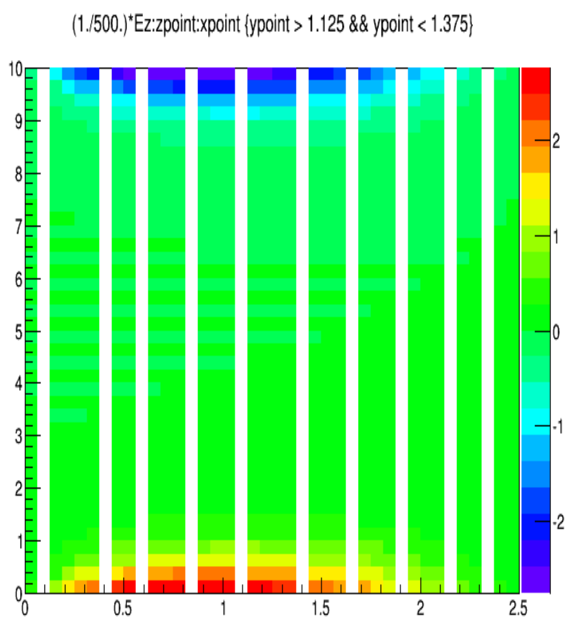
E_y
Before
Interp-
olation

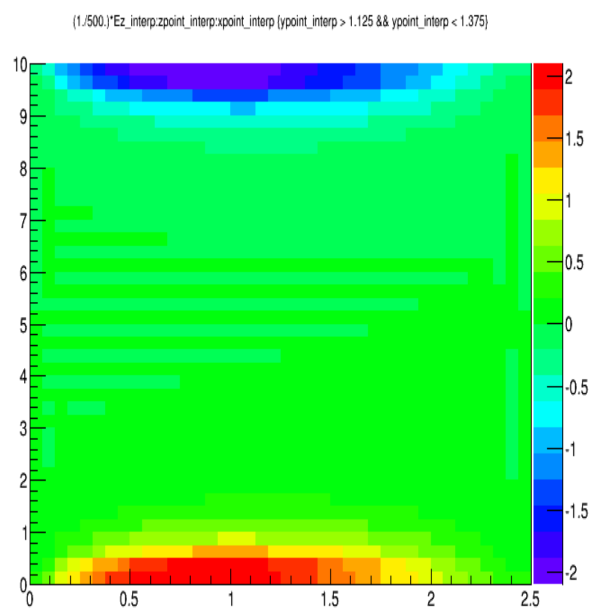




E_y
After
Interp-
olation

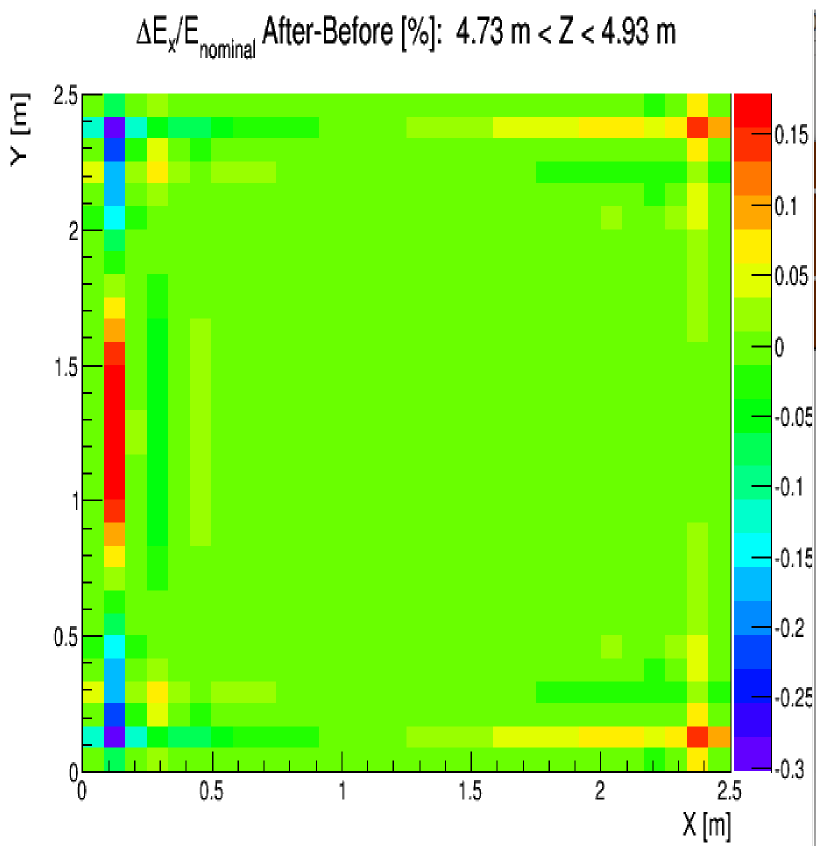
E_z
Before
Interp-
olation

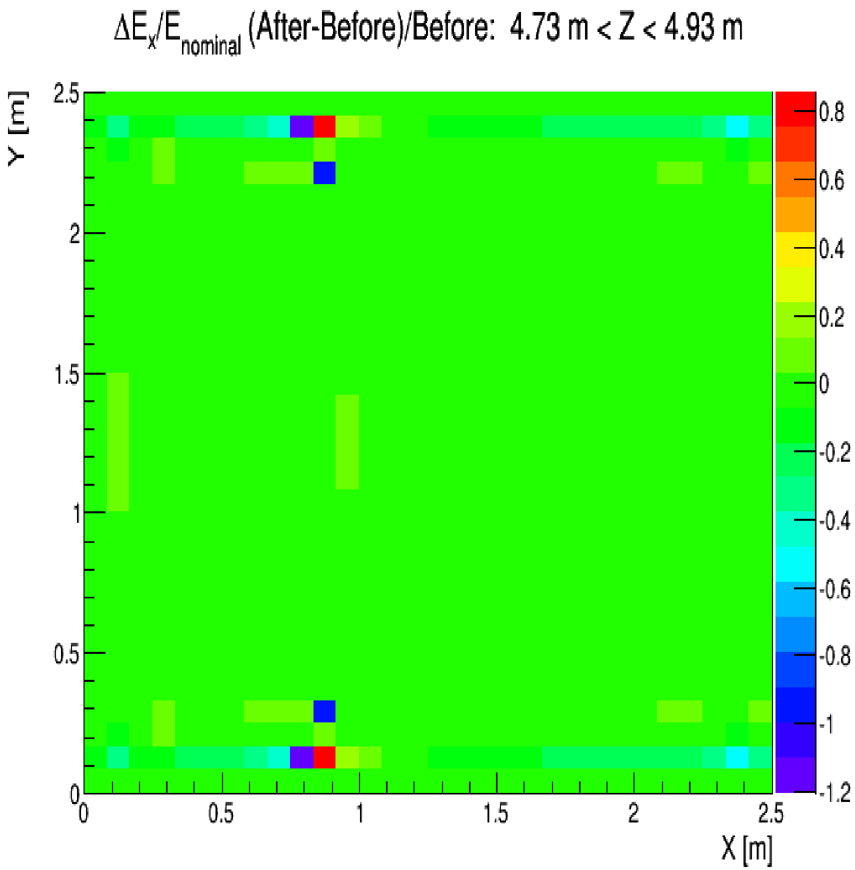




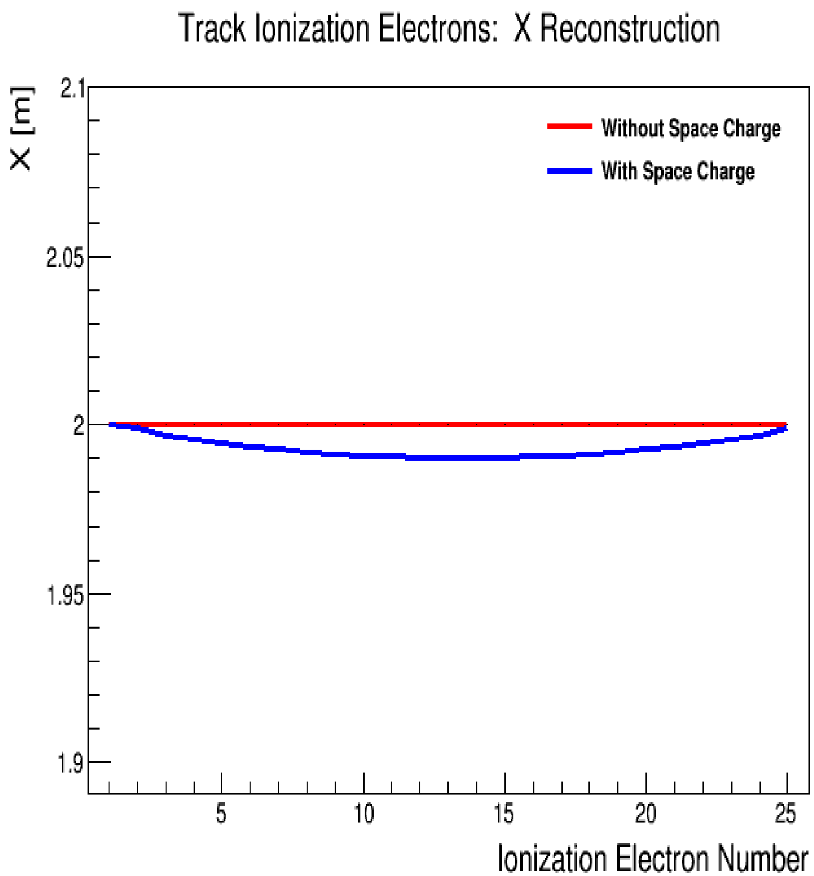
E_z
After
Interp-
olation

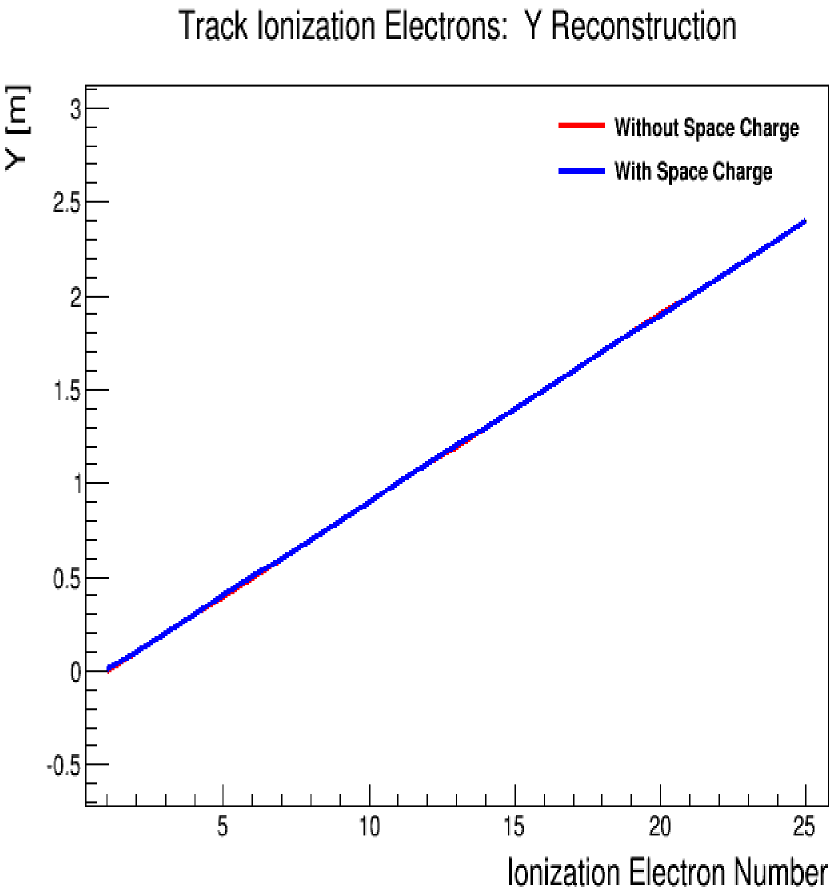
E Field Interp. Uncert.

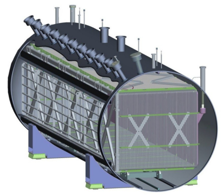




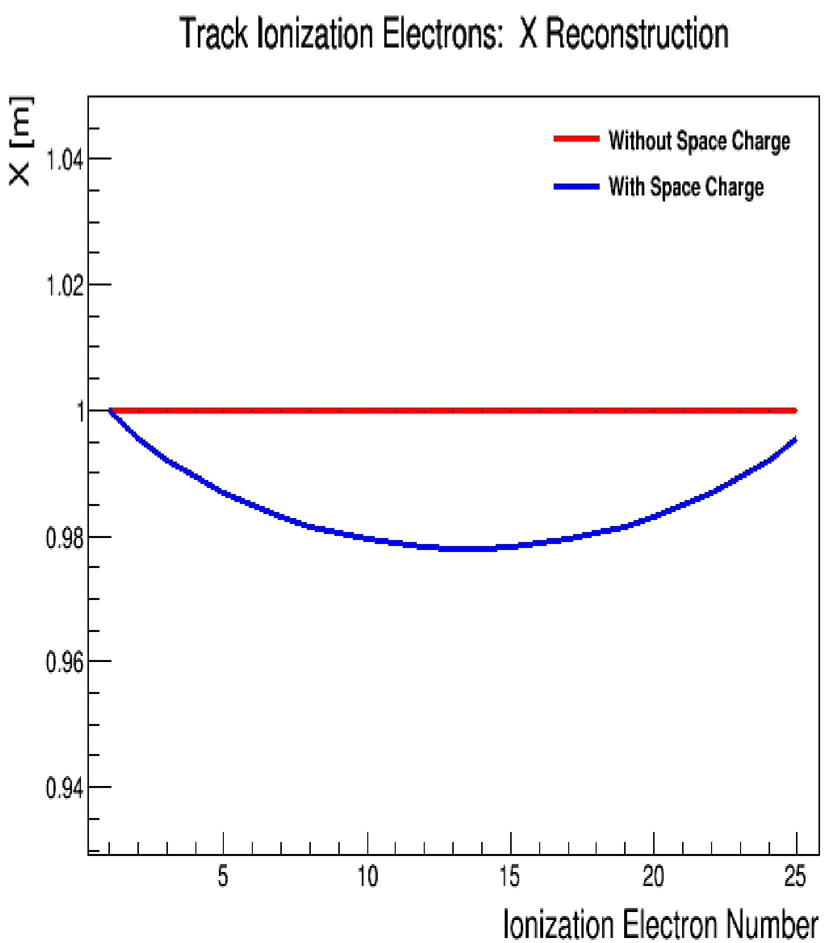
Sample Track: x = 2 m

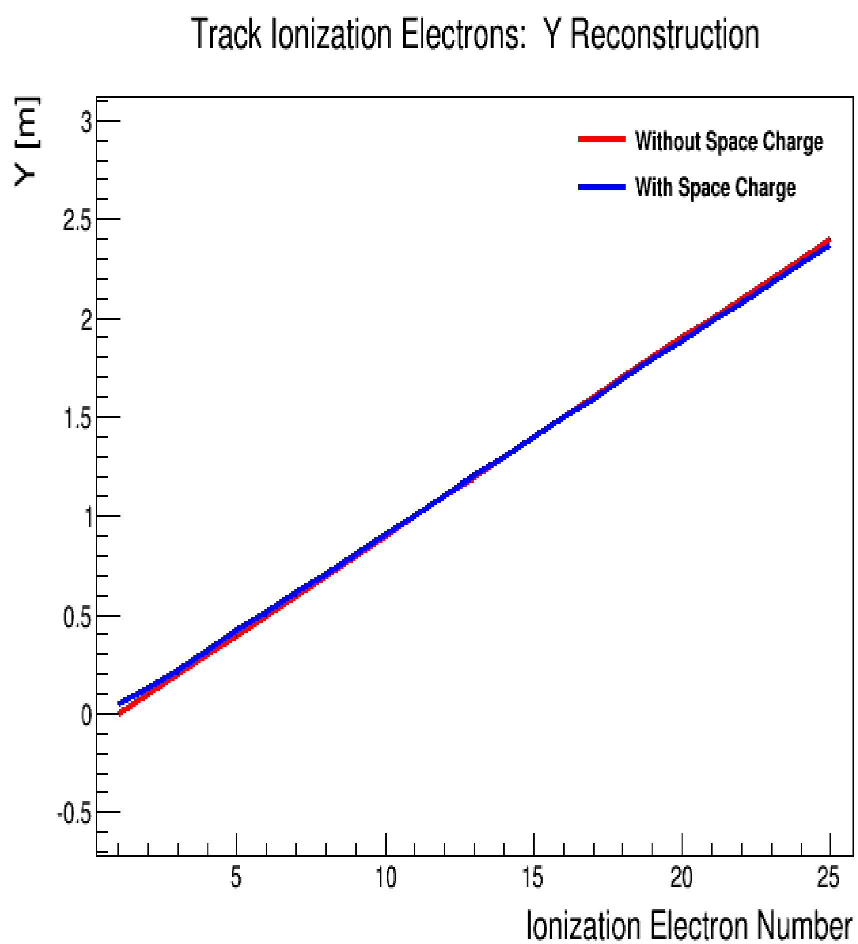


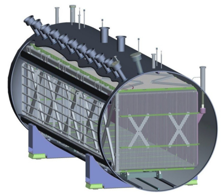




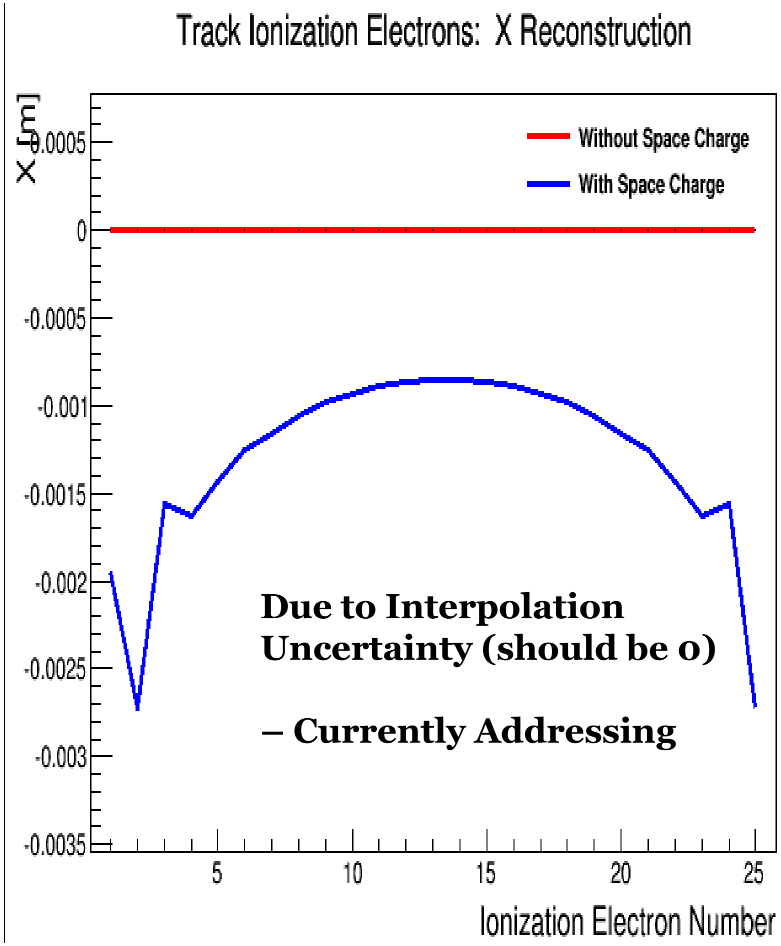
Sample Track: x = 1 m

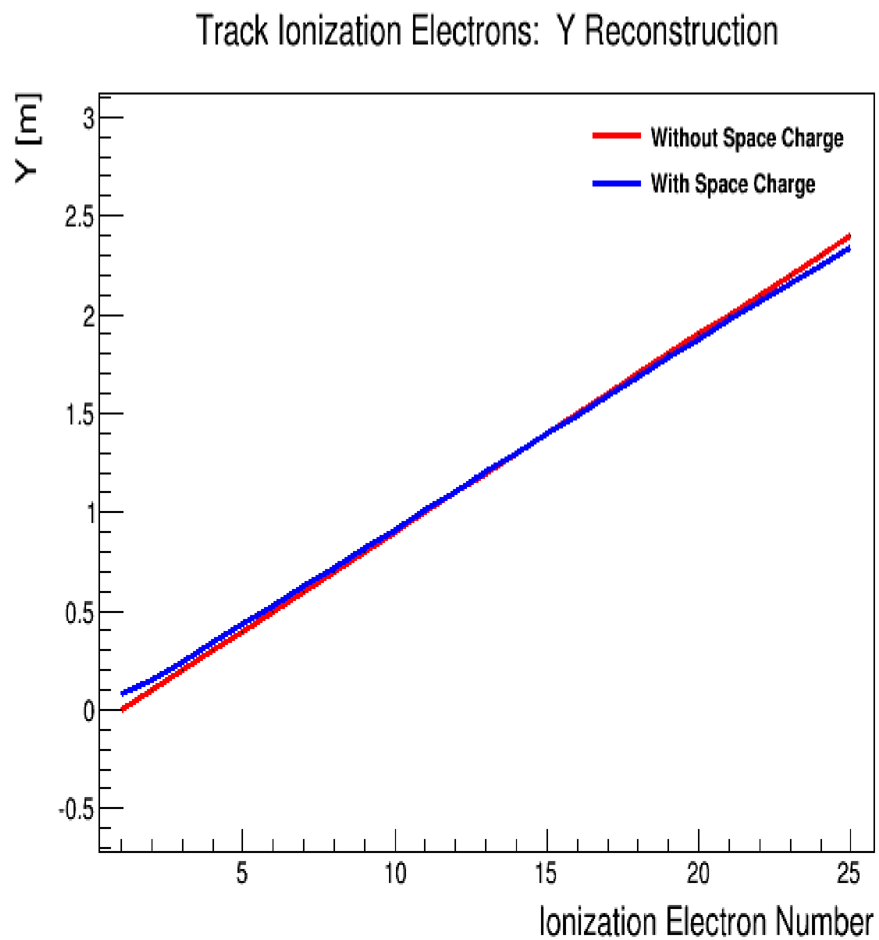






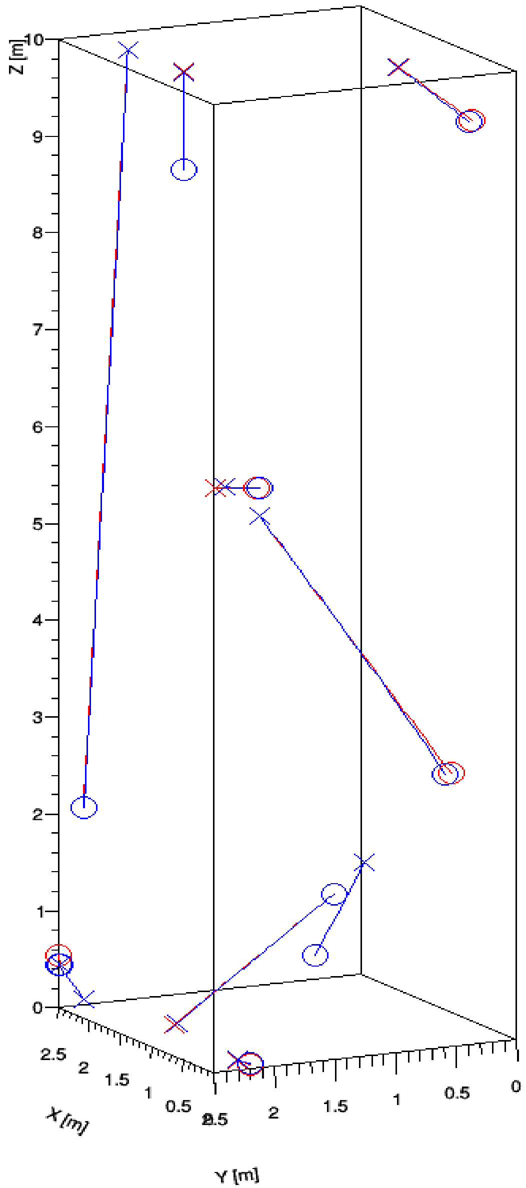
Sample Track: x = 0 m

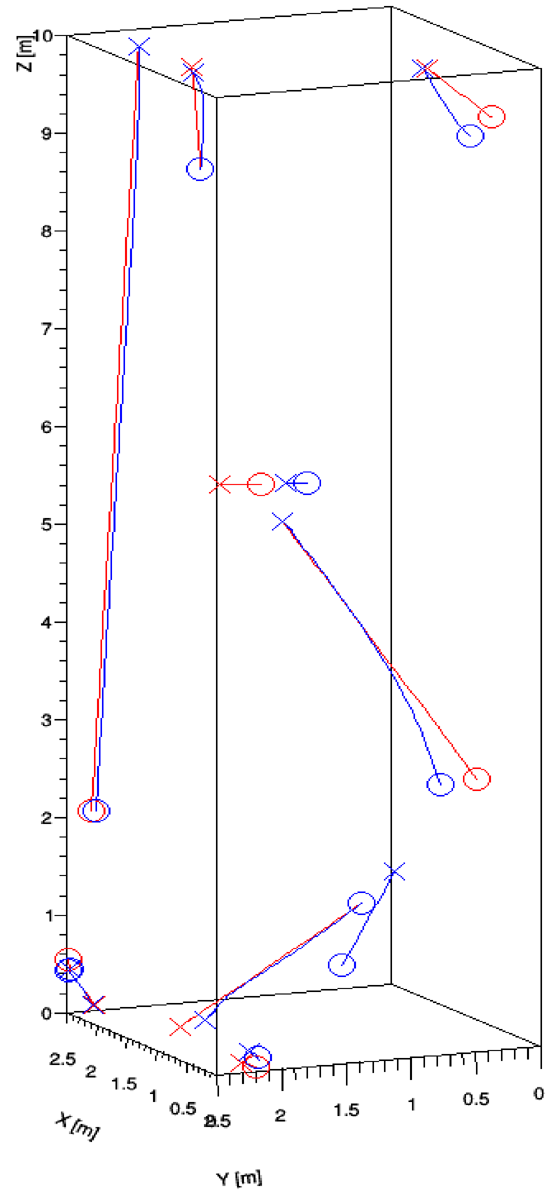




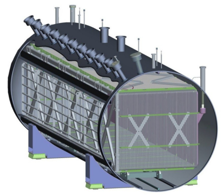
Sample "Cosmic Event"

Nominal Space Charge Deposition Rate



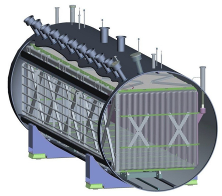


10X Space Charge Deposition Rate

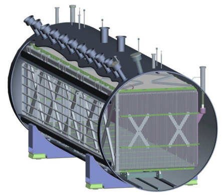


Plans

- Allow for arbitrary space charge configuration
  - Or just change E fields by hand to study calibration techniques
- Improve interpolation scheme
  - Include points outside of boundary from Fourier series solution
- Reduce runtime of ray-tracing
  - Simple ways to improve
  - Will discuss details at later meeting
- Study calibration techniques using this **simple** tool
  - Use ensemble of "cosmic events" as shown in previous slide

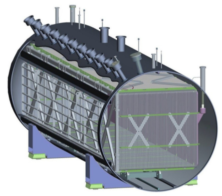


BACKUP SLIDES



Relevant Numbers

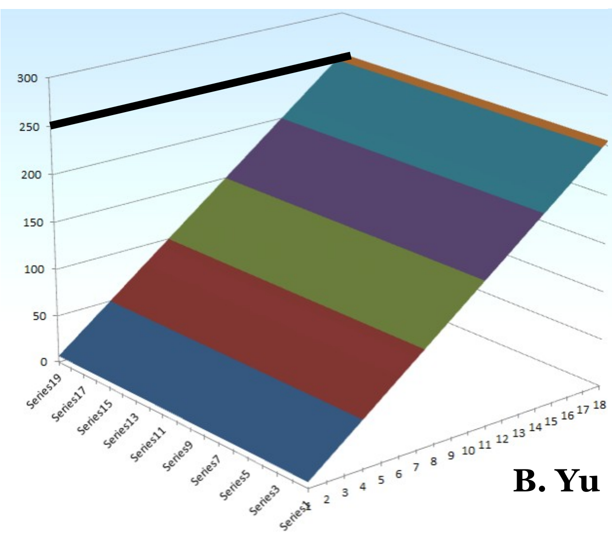
- Nominal electron drift velocity: **1.6 mm/μs**
- Ion drift velocity: **8 mm/s**
- Cosmic muon flux:
  - Vertical: **200/m²/s**
  - Horizontal: **60/m²/s**
- Max ion charge density in LAr: **90 nC/m³**
- Expected modification to E field strength (both in drift direction and laterally, compared to nominal drift E field of 500 V/cm):
  - Typical: **5%** (both up and down)
  - Maximal: **10%** (both up and down)
- Expected effects on reconstructed electron position:
  - Drift direction: **1.5 cm** (worst case)
  - Lateral directions: **10 cm** (worst case)



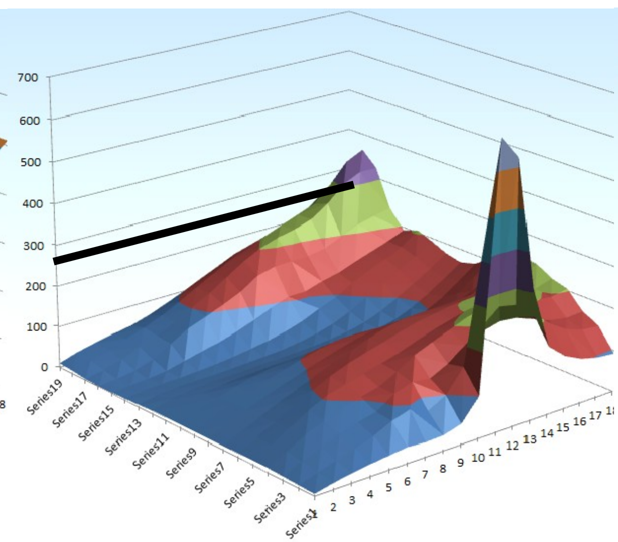
Complications

- Previous studies have been 2D… differences in 3D?
- Not accounting for non-uniform charge deposition rate in detector → significant fluctuations?
- Flow of liquid argon → likely significant effect!
  - Time dependencies?

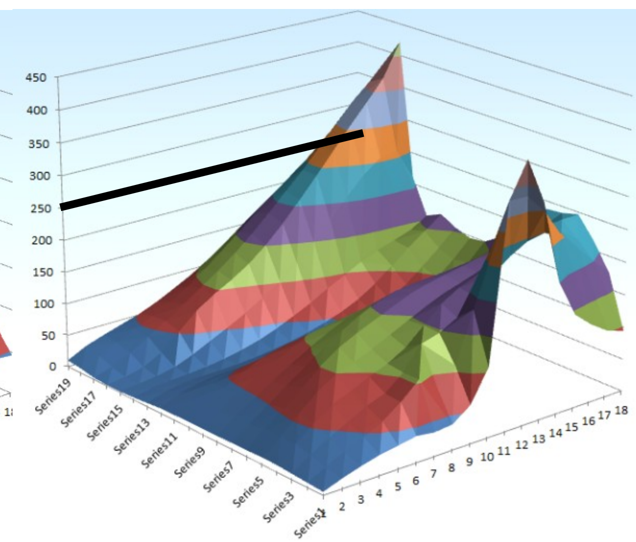
No Flow



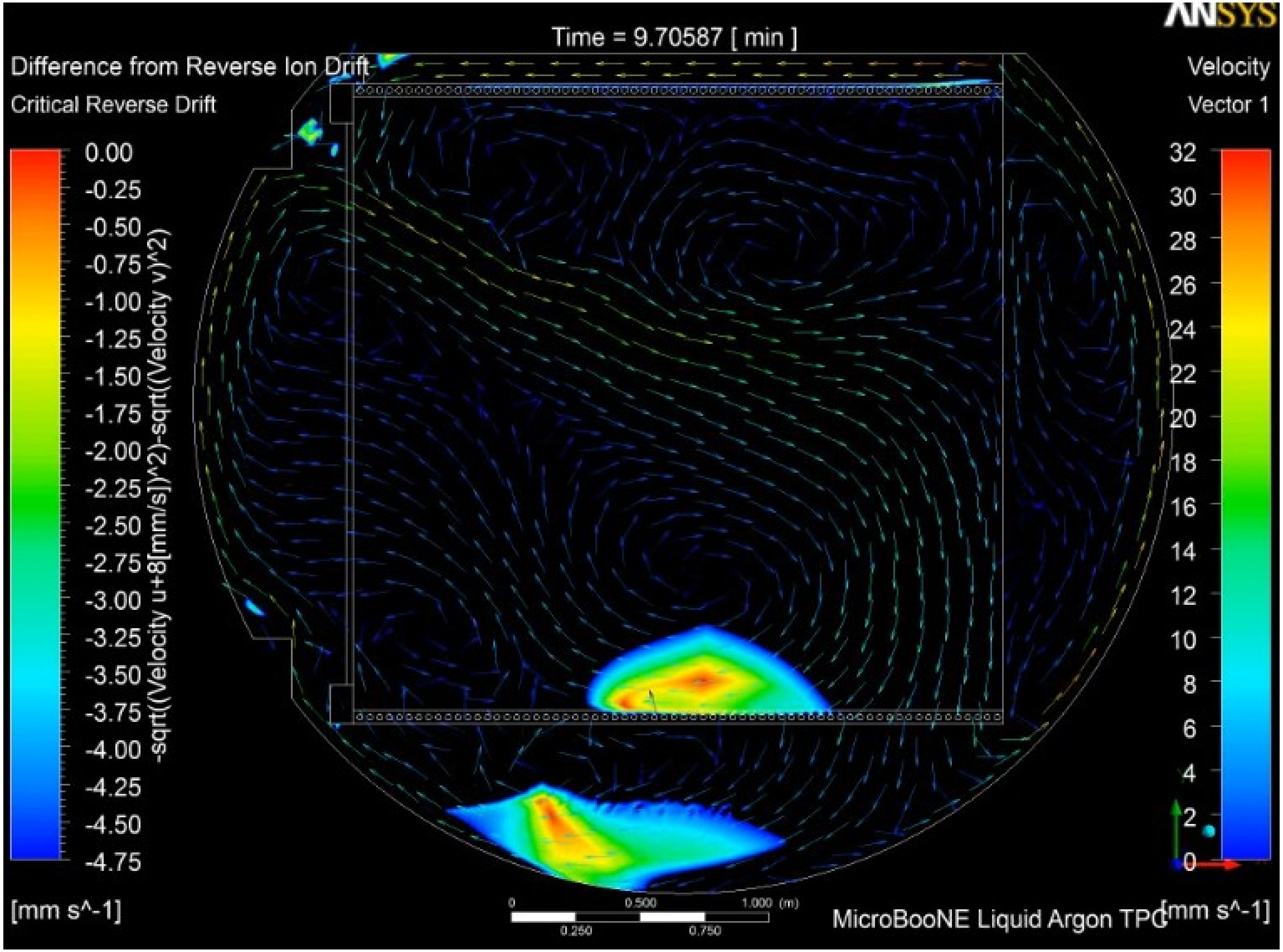
Flow w/o Turbulence



Flow w/ Turbulence



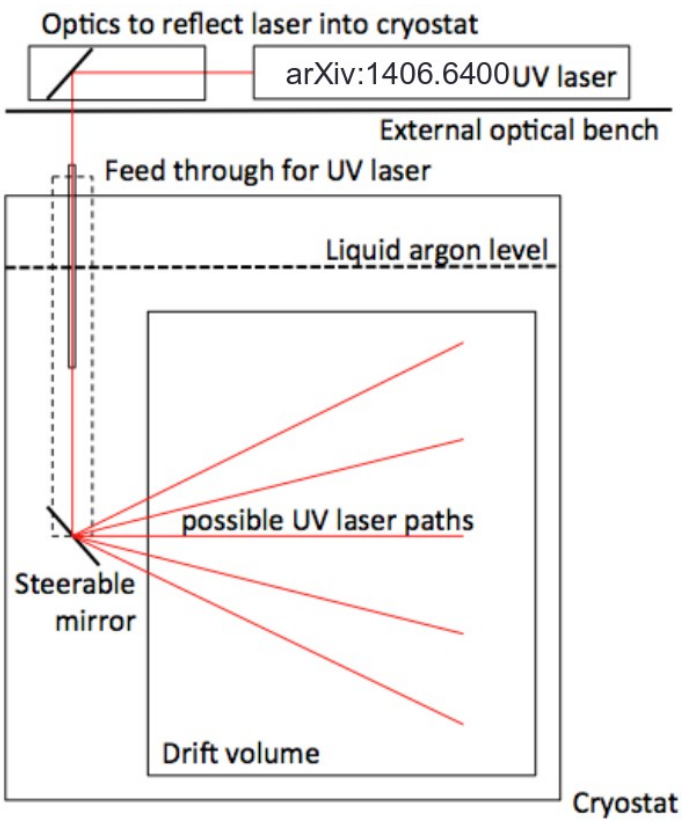
Liquid Argon Flow

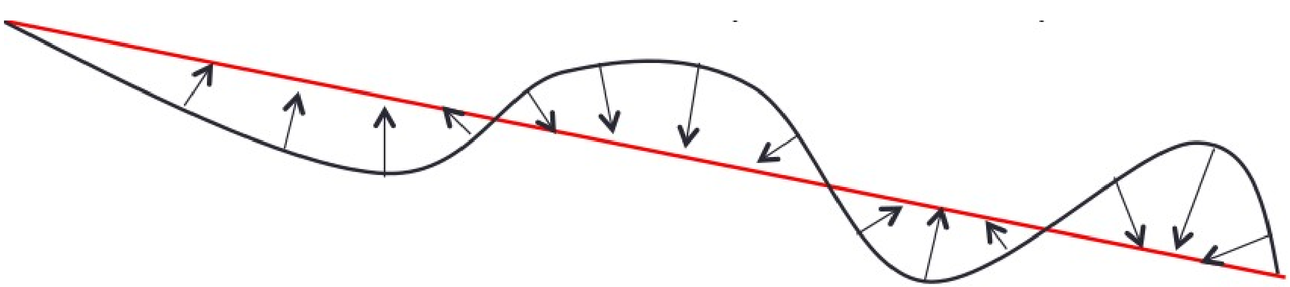


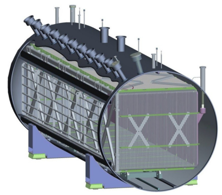
B. Yu

Laser System Calib.

- Can use laser system for calibrations, but:
  - Only once per day
  - Limited set of laser paths
  - Ambiguity of observed charge origin within path of laser
- Intersection of two laser beams would remove ambiguity
  - Is this possible in our setup?
- How best to use laser calibration observations to make corrections?







Cosmics: In Situ Calib.

- Can also use cosmic muon tracks for calibration
  - Advantages:
    - Can sample smaller time scales more relevant for a particular neutrino-crossing time slice
    - Possible data-driven cross-check against laser system calibration
  - Difficulties:
    - Not exactly clear what best approach is
- Idea: use lateral charge displacement at track ends
  - No timing offset at detector edges (drift E field unchanged)